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On the origin of the circular polarization in radio pulsars

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ABSTRACT
Properties of circularly polarized waves are studied in the pulsar magnetosphere plasma. It is shown that some observational characteristics of the circular polarization observed in the pulsar radio emission can be qualitatively explained in the framework of the model based on anomalous Doppler resonance. Performed analysis provides that if the difference between Lorentz factors of electrons and positrons is relatively high, one of the circularly polarized waves becomes super-luminal and therefore can not be generated by cyclotron instability. We suggest that this case corresponds to the pulsars with the domination of one hand of circular polarization through the whole averaged pulse profile at all observed frequencies. For intermediate values of the difference between Lorentz factors both circularly polarized waves are generated, but the waves of one handness are much more effectively generated for high frequencies, whereas generation of another handness dominates for low frequencies. This should correspond to the pulsars with strong frequency dependence of the degree of circular polarization. The case of relatively small difference between Lorentz factors corresponds to the pulsars with sign reversal of the circular polarization in the centre of averaged pulse profiles.

Key words: pulsars: general: radio emission – polarization.

1 INTRODUCTION

Radio emission from pulsars is highly polarized. In some cases the fraction of linear polarization in the total radio emission is close to 100 %. On the other hand, the circular polarization V is the highest among observed natural sources of electromagnetic radiation. Observations of circular polarization of individual pulses (Clark & Smith 1969; Manchester et al. 1975; Han et al. 1998; Karastergiou et al. 2003; Karastegiou & Jonston 2004) show high degree of V, usually several tens of per cent and very irregular structure of circular polarization through the pulse.

Significant circular polarization is also usually observed in the average pulse profiles of most pulsars. However, as a rule averaged profiles have much smaller degree of circular polarization then individual pulses. It tends to peak near the centre of the averaged pulse profile. In many pulsars the circular polarization reverses its sign near the centre, while in other pulsars the same sign of V retained throughout. According to Radhakrishnan & Rankin (1990) these two types of circular polarization behavior are called 'antisymmetric' and 'symmetric' types respectively. The pulsars with the symmetric circular polarization often show strong frequency dependence of the degree of circular polarization.

In spite of extensive observational data even the origin of high circular polarization in pulsar radio emission remains mainly unclear. Usually it is supposed that the circular polarization is related to either the pulsar radio emission mechanism or propagation effects in the pulsar magnetosphere (Cheng & Ruderman 1979; Melrose & Luo 2004). Cheng & Ruderman (1979) suggested that asymmetry between electrons and positrons in the magnetosphere plasma converts linear polarization into circular one during electromagnetic wave propagation in the magnetosphere. According to another model (Kazbegi et al. 1991), cyclotron instability is responsible for the observed circular polarization in pulsar radio emission. As it was shown by Kazbegi et al. (1991), due to the relative motion of electrons and positrons that was supposed by Cheng & Ruderman (1977), two circularly polarized electromagnetic waves can exist in the pulsar magnetosphere for relatively small angles of propagation with respect to the pulsar magnetic field. According to this model these circularly polarized waves are generated by cyclotron instability. In the framework of this model, the antisymmetric type circular polarization is a consequence of relative drift motion of electrons and positrons in the curved magnetic field. In general it seems that both generation and propagation effects should contribute to the observed circular polarization of pulsars.

In the presented paper we study properties of circularly polarized waves in the magnetosphere plasma and ignore propagation effects. Performed analysis provides that if the

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difference between Lorentz factors of electrons and positrons is relatively high, one of the circularly polarized waves becomes super-luminal and therefore can not be generated by kinetic mechanisms, such as cyclotron instability. We suggest that this case corresponds to the pulsars with symmetric circular polarization profiles that shows the domination of one handness circular polarization at all observed frequencies. For intermediate values of the difference between Lorentz factors both of circularly polarized waves are generated, but the waves of one handness are much more effectively generated for high frequencies, whereas generation of another handness dominates for low frequencies. This should correspond to the pulsars with symmetric circular polarization profiles that shows strong frequency dependence of the degree of circular polarization. The case of relatively small difference between Lorentz factors was discussed by Kazbegi et al. (1991) and corresponds to the pulsars with antisymmetric circular polarization profiles.

The paper is organized as follows. Properties of circularly polarized waves in the magnetosphere plasma are discussed in section 2. Different regimes of cyclotron instability development are studied in section 3. The conclusions are summarized in section 4.

2 CIRCULARLY POLARIZED WAVES IN THE MAGNETOSPHERE PLASMA

It is generally assumed that the pulsar magnetosphere is filled by dense relativistic electron-positron plasma flowing along the open magnetic field lines, which is generated as a consequence of the avalanche process first described by Goldreich & Julian (1969) and developed by Sturrock (1971). This plasma is multi-component (see, e.g., Arons 1981), with a one-dimensional distribution function, containing: (i) electrons and positrons of the bulk of plasma with mean Lorentz factor of γ_p and density n_p; (ii) particles of the high-energy 'tail' of the distribution function with γ_t and n_t, stretched in the direction of positive momenta; (iii) the ultrarelativistic ($\gamma_b \sim 10^6$) primary beam with so called 'Goldreich-Julian' density $n_b \approx 7\times10^{-2}B_0P^{-1}(R_0/r)^3\,\mathrm{cm}^{-3}$ (where P is a pulsar period, R_0 is a neutron star radius, B_0 is a magnetic field value at the stellar surface and r is a distance from the neutron star's centre), which is much less than n_p ($\kappa \equiv n_p/n_b \gg 1$). The one dimensional distribution function of electrons f_- and positrons f_+ are shifted with respect to each other due to the presence of the primary beam and quasi neutrality of the plasma. The value

$$\Delta\gamma = \gamma_+ - \gamma_- = \int f_+\gamma dp_\| - \int f_-\gamma dp_\|, \tag{1}$$

is small but of decisive significance in explaining of the polarization properties of pulsars. The distribution functions are normalized such that $\int f_\pm dp_\| \equiv 1$.

For clarity we assume that the primary beam consists of particles with positive charge. In this case according to Cheng & Ruderman (1977)

$$\Delta\gamma \approx \gamma_p^4/\gamma_b > 0. \tag{2}$$

An extensive analysis have been conducted (Volokitin et al. 1985; Arons & Bernard 1986; Kazbegi et al. 1991) in order to study the dispersion properties of the waves propagating through the highly magnetized relativistic electron-positron plasma of pulsar magnetosphere. If the z axis is directed along the pulsar magnetic field and the wave vector $\mathbf{k}$ is assumed to lie in the (y,z) plane, and the drift motion of the plasma particles due to the curvature of the magnetic field is neglected, the components of permittivity tensor are (Kazbegi et al. 1991):

$$\epsilon_{xx} = \epsilon_{yy} = 1 - \frac{1}{2}\sum_\alpha \frac{\omega_{p\alpha}^2}{\omega^2}\int\frac{dp_z}{\gamma}(\omega - k_z v_z)A_\alpha^+ f_\alpha, \tag{3}$$

$$\epsilon_{zz} = 1 - \sum_\alpha \omega_{p\alpha}^2\int\frac{dp_z f_\alpha}{\gamma^3(\omega - k_z v_z)^2}, \tag{4}$$

$$\epsilon_{yx} = -\epsilon_{xy} = \frac{i}{2}\sum_\alpha \frac{\omega_{p\alpha}^2}{\omega^2}\int\frac{dp_z}{\gamma}(\omega - k_z v_z)A_\alpha^- f_\alpha, \tag{5}$$

$$\epsilon_{zx} = -\epsilon_{xz} = \frac{i}{2}\sum_\alpha \frac{\omega_{p\alpha}^2}{\omega^2}\int\frac{dp_z}{\gamma}k_y v_z A_\alpha^- f_\alpha, \tag{6}$$

$$\epsilon_{yz} = \epsilon_{zy} = -\frac{i}{2}\sum_\alpha \frac{\omega_{p\alpha}^2}{\omega^2}\int\frac{dp_z}{\gamma}k_y v_z A_\alpha^+ f_\alpha, \tag{7}$$

where

$$A_\alpha^\pm \equiv \frac{1}{\Omega_\alpha^-} \mp \frac{1}{\Omega_\alpha^+},\quad \Omega_\alpha^\pm \equiv \omega - k_z v_z \pm \frac{\omega_{B\alpha}}{\gamma}, \tag{8}$$

and

$$\omega_{p\alpha}^2 \equiv \frac{4\pi e^2 n_\alpha}{m},\quad \omega_{B\alpha} \equiv \frac{e_\alpha B}{mc} \tag{9}$$

are plasma and cyclotron frequencies of corresponding kind of particles respectively.

Introducing the system with z' axis directed along $\mathbf{k}$ the equations for waves in the plasma takes the form:

$$\left[(k'^2\delta_{lm} - k'_l k'_m)\frac{c^2}{\omega^2} - \epsilon'_{lm}\right]E'_m = 0. \tag{10}$$

The radio emission is thought to be due to one of several possible instabilities in which the distribution of particles causes waves in a specific wave mode to grow. These waves then propagate in the pair plasma of a pulsar magnetosphere, transform into vacuum-like electromagnetic waves as the plasma density drops, enter the interstellar medium, and reach an observer as the pulsar radio emission.

In the general case of oblique propagation with respect to the magnetic field three different wave modes can be distinguished. One of these modes is the super-luminous O-mode. Identification of the other modes depends on the angle θ between $\boldsymbol{k}$ and $\boldsymbol{B}$, where $\boldsymbol{k}$ a wave-vector and $\boldsymbol{B}$ is a local magnetic field. If

$$\theta^2 \gg \frac{\omega}{\omega_B}\frac{\Delta\gamma}{\gamma_p^4} \equiv \theta_0^2, \tag{11}$$

where $\omega_B \equiv |e|B/mc$, there exists two linearly polarized waves: the purely electromagnetic X-mode and the subluminous Alfvén (A) mode. The A mode, as well as O-mode, are of mixed electrostatic-electromagnetic nature. Electric field vectors of the O and A-modes lie in the $(\boldsymbol{k}\,\boldsymbol{B})$ plane, while the electric field of the X-mode perpendicular to this plane.

In the opposite limiting case

$$\theta^2 \ll \theta_0^2, \tag{12}$$

there exist two circularly polarized waves with left-handed and right-handed polarization. In the case of propagation along $\boldsymbol{B}$, according to equations (3)-(7) and (10) dispersion equations for these waves are:

$$\frac{k^2c^2}{\omega^2} = \epsilon_{xx} \pm i\epsilon_{xy} = 1 - \sum_\alpha \frac{\omega_{p\alpha}^2}{\omega^2} \int \frac{dp_z}{\gamma} \frac{\omega - kv}{\Omega_\alpha^\pm} f_\alpha. \tag{13}$$

Assuming $\omega/2\gamma|\omega_{B\alpha}| \ll 1$ and expanding the integrand in the series with respect to this small parameter we obtain:

$$\omega_{1,2} = kc(1-\delta) \pm \Delta\gamma\omega_B\delta, \tag{14}$$

where $\delta \equiv \omega_p^2/4\gamma_p^3\omega_B^2$ and upper sign corresponds to right handed circularly polarized wave.

Analysis of cyclotron resonance condition

$$\omega - k_z v_z \pm \frac{\omega_{B\alpha}}{\gamma} = 0 \tag{15}$$

provides (Machabeli & Usov 1989), that the wave are generated only at anomalous Doppler effect [i.e., when the third term in equation (15) is positive]. Consequently, left and right-handed circularly polarized waves are excited by resonant positrons and electrons respectively. It can be readily shown, that only the particles of the tale and primary beam are involved in this process. The growth rate of the instability is

$$\Gamma \approx \frac{\pi}{2} \frac{\omega_{p,res}^2}{\omega_0 \gamma_{T,res}}, \tag{16}$$

where ω_0 is the resonant frequency

$$\omega_0 \approx \frac{\omega_B}{\delta\gamma_{res}}, \tag{17}$$

and $\gamma_{T,res}$ and γ_{res} are thermal spread and average Lorentz factors of the resonant particles respectively. Cyclotron resonance with the particles of the bulk of plasma causes the damping of the waves with the decrement

$$\Gamma' \approx -\frac{\pi}{2} \frac{\omega_p^2}{\omega_0' \gamma_p}, \tag{18}$$

where the frequency of the damped waves $\omega_0' \sim 2\gamma_p\omega_B$.

Kazbegi et al. (1991) suggested that the 'core' component of pulsar emission is generated via the cyclotron instability. Electromagnetic waves are generated at the distance of several hundred neutron star radii above the surface. In the framework of this model the sign reversal of the circular polarization, frequently observed near the centre of mean pulse profile, is caused by drift motion of electrons and positrons in the curved magnetic field. As it was mentioned above, the effects of the curvature drift motion of the particles are not considered in the presented paper.

In the next section we will show, that main properties of the two groups of pulsars, that have high circular polarization component either of one sign for the whole frequency range or different sign of circular polarization for different frequencies, can also be naturally explained in the framework of this model.

3 DIFFERENT REGIMES OF THE CYCLOTRON INSTABILITY DEVELOPMENT

As it was mentioned above, the electromagnetic waves can be generated only by cyclotron resonance at anomalous Doppler effect. As it can be readily seen, this means that only the generation of sub-luminal waves is possible. Equation (14) shows, that in the presence of the relative motion of electrons and positrons ($\Delta\gamma \neq 0$) the waves in the magnetosphere can be sub-luminal as well as super-luminal. If $kc < \Delta\gamma\omega_B$, the right-handed circularly polarized wave becomes super-luminal and therefore can not be generated by cyclotron instability (note, that if $\Delta\gamma$ defined by equation (1) is negative, then the same is true for left-handed circularly polarized wave). Consequently, the development of the cyclotron instability strongly depends on parameter

$$\Upsilon \equiv \frac{\Delta\gamma}{2\gamma_p} \frac{2\gamma_p\omega_B}{\omega}. \tag{19}$$

The second multiplier in the right hand side of this equation $2\gamma_p\omega_B/\omega \gg 1$, according to assumption made for derivation of dispersion relation (14). Estimation of the first multiplier $\Delta\gamma/\gamma_p$ is much more complicated. According to Ruderman & Sutherland (1975) model

$$\gamma_b \approx 3 \cdot 10^6 \left(\frac{B_0}{10^{12}\ \mathrm{G}}\right)^{-1/7} \left(\frac{P}{1\ \mathrm{sec}}\right)^{-1/7} \left(\frac{R_c}{R_0}\right)^{4/7}, \tag{20}$$

where R_c is curvature radius of the magnetic field lines at the surface of the pulsar. If the magnetic field of pulsar is strongly dipole and $R_c \sim R_0$, then $\gamma_p \sim 10^2$ and equation (2) yields $\Delta\gamma/\gamma_p \sim 1$. On the other hand, Machabeli & Usov (1989) shown that if the magnetic field of the pulsar has significant quadrupole component at the surface of the pulsar, then

$$\gamma_p \approx 3\frac{R_c}{R_0}\left[1 + \left(\frac{B_0}{2 \cdot 10^{12}\ \mathrm{G}}\right)^2\right]^{-1/2}, \tag{21}$$

and for $R_c \sim R_0$ we obtain $\Delta\gamma/\gamma_p \sim 10^{-4}$. Consequently, in principle Υ can vary in the wide range from 10^{-3} to 10^2 and different regimes of the cyclotron instability development should be considered separately.

3.1 The case $\Upsilon \ll 1$

Substituting equation (14) into the resonant condition at anomalous Doppler effect and assuming $\delta \gg 1/2\gamma_{res}^2$ we obtain for the resonant frequencies

$$\omega_{1,2,res} \approx \frac{\omega_B}{\delta\gamma_{res}} \mp \Delta\gamma\omega_B. \tag{22}$$

The case $\Upsilon \ll 1$ was considered in Kazbegi et al. (1991). In this limiting case according to the last equation left and right handed circularly polarized waves are generated by cyclotron instability with approximately same frequencies and growth rates. In the framework of this model the sign reversal of the circular polarization, frequently observed near the centre of mean pulse profile, is caused by drift motion of electrons and positrons in the curved magnetic field of pulsar.

3.2 The case $\Upsilon > 1$

In the case $\Upsilon > 1$, right-handed circularly polarized wave become super-luminal and consequently the resonant condition at anomalous Doppler effect can not be fulfilled for this wave mode. Therefore only left-handed circularly polarized waves are generated by cyclotron instability. In the framework of the presented model this situation is realized in the pulsars that have strong domination of one of the circularly polarized component along the whole averaged pulse profile for all observed frequencies, such as PSR B1913+10, PSR B1914+13 and PSR B1356-60 (Han et al. 1998). This suggestion is supported by the fact, that the pulsars of this group as a rule have high or extremely high degree of circular polarization ($\langle |V| \rangle / S > 15\%$). Indeed, as it was mentioned in the previous section, circularly polarized waves exist only in the small angle θ_0 with respect to the pulsar magnetic field. According to equation (12) the value of θ_0 as well as Υ is proportional to $\Delta\gamma$, and therefore proposed model predicts that pulsars with strong domination of one circularly polarized component should have relatively high degree of circular polarization.

3.3 The case $0.1 < \Upsilon < 1$

We suggest that the pulsars that shows strong frequency dependence of the circular polarization has $0.1 < \Upsilon < 1$ in the wave generation region. In this range of parameters waves with both left and right-handed circularly polarized waves are generated by cyclotron instability, but there exists significant difference between resonant frequencies given by equation (22) and corresponding growth rates (17). One also has to note, that the resonant frequencies as well as the decrements vary with distance from the pulsar surface. Therefore, in general quite complicated picture of circular polarization dependence on frequency can be supposed. However, the qualitative picture of the frequency dependence of radio emission circular polarization of such pulsars should be the following: in case of positive $\Delta\gamma$, at low and high frequencies right-handed and left-handed circular polarization should strongly dominate, whereas in the range of middle frequencies some soft transition between these two regimes should be observable. This qualitative picture is in good accordance with observations of pulsars that shows strong frequency dependence of circular polarization, e.g., PSR B1749-28 and PSR B1240-64. According to the presented model, due to the reasons discussed in the previous subsection, these pulsars also should have relatively high degree of circular polarization. It seems that, existing observations confirm this feature (Han et al. 1998).

It should be noted that analysis presented in the beginning of this section shows that $\Delta\gamma/\gamma_p$ is mainly determined by two unmeasurable variables: the ratio R_c/R_0 and the ratio of dipole and quadrupole components of the magnetic field at the surface of the pulsar, whereas its dependence on measurable quantities, such as P and $\dot{P}$ is very weak. Consequently, direct comparison with observational data seems to be very difficult and only indirect analysis presented above could be performed for qualitative comparison of the predictions of the presented model with observations.

4 CONCLUSIONS

In this paper we attempt to explain observed properties of the circular polarization in radio emission of pulsars in the framework of the model that involves generation of circularly polarized waves in the magnetosphere by cyclotron instability. Relative motion of electrons and positrons in the magnetosphere plasma is responsible for existence of tho circularly polarized waves that are generated by cyclotron instability. According to resonant condition at anomalous Doppler effect, the critical parameter that determines the character of cyclotron instability development is Υ defined by equation (19). If $\Upsilon > 1$, one of the waves becomes super-luminal and therefore can not be generated by cyclotron instability. In our opinion this case is realized in the pulsars that have strong domination of one of the circularly polarized component along the whole averaged pulse profile for all observed frequencies. When $0.1 < \Upsilon < 1$, waves with both left and right-handed circular polarization are effectively generated, but there exists significant difference between resonant frequencies given by equation (22). This corresponds to the pulsars with strong frequency dependence of circular polarization profiles. And finally, the case $\Upsilon \ll 1$ is realized in pulsars with asymmetric circular polarization profiles.

Explanation of observed circular polarization of pulsars should include both generation and propagation effects. While in the present paper we focus on generation effects, the propagation effects of the waves in the magnetosphere plasma will be described in the consequent paper. relevant studies are under way presently.

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